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REAL-TIME CONCENTRATION MONITORING OF LARGE AERODYNAMIC DIAMETER FIBER AEROSOLS USING THE GEOMETRIC OPTIC INVERSION TECHNIQUE

R. J. Wright
J. F. Embury, Ph.D.
D. H. Anderson

RESEARCH DIRECTORATE

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Wright, R.J.; Embury, J.F., Ph.D.; and Anderson, D.H.

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Characterization of screening aerosols requires a measurement of the concentration of the aerosol cloud. For large aerodynamic diameter materials this is not always feasible. An alternate method, using geometric optic inversion, is described and derived. This inversion employs measurement of the transmission through the material by a short wavelength energy beam, such as Helium Neon laser. The transmission is then used to calculate the concentration of the material. Cloud concentrations calculated by this method are compared to measured concentrations, employing a unique sampling filter.

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PREFACE

The work described in this report was authorized under Project No. 1C162622A552, Smoke and Obscurants. This work was started in May 1986 and continues as of June 1990.

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REAL-TIME CONCENTRATION MONITORING OF LARGE AERODYNAMIC DIAMETER FIBER AEROSOLS USING THE GEOMETRIC OPTIC INVERSION TECHNIQUE

1. INTRODUCTION

Characterization of screening aerosol materials often requires dissemination of the material into a test chamber and measurement of its screening efficiency at various wavelengths of radiant energy. One measure of the aerosol screening efficiency is the extinction coefficient, which requires knowledge of the material concentration in the chamber. This is a relatively straightforward measurement for small aerodynamic diameter particles, involving mass aerosol sampling onto a weighed filter. However, attempts to measure the concentration of large aerodynamic diameter particles often results in a lower-than-actual concentration measurement, and therefore, a higher-than-actual extinction coefficient. This report presents an alternate method for measuring concentration based on transmissometry rather than filter sampling. This method is especially useful with large aerodynamic diameter particles which are monodisperse. Commercially available chopped fibers (flock) have a relatively large aerodynamic diameter and represent the only readily available aerosol that is monodisperse.

Calculation of the extinction coefficient (α) involves determination of three parameters: transmittance (T), pathlength (L), and concentration (C). Transmittance is the ratio of intensity through an aerosol cloud to the intensity when no aerosol is present. This is a straightforward, continuous, real-time measurement at any wavelength of incident energy. Pathlength is the distance that the incident beam traverses the aerosol cloud. Aerosol concentration (C) is calculated from four measured quantities; filter weight (m_f), filter plus aerosol loading weight (m_l), air volume flow rate through the filter ($\dot{V}$), and sampling time (t).

$$C = \frac{m_l - m_f}{\dot{V}t} \tag{1}$$

Measurement of the concentration by a filter sample is not very accurate when characterizing large particles. The difficulties involved with measuring aerosol concentration of large aerodynamic diameter particles are twofold. One difficulty arises in the collection of particles onto a filter when the particles are too large to follow the streamlines into the sampling mechanism. The momentum of such particles in the aerosol cause them to avoid being sampled. The other difficulty is caused by the particles failing to remain on the sampling filter. They either bounce off during sampling, fall off, or are blown off after sampling is concluded. Both difficulties result in a lower sampled mass of material, and, therefore, a lower concentration calculation. When this low concentration is inserted into the equation for extinction coefficient, the resulting extinction calculation is erroneously high.

2. APPROACH

Fortunately, there is an alternative method to obtain aerosol concentration; however, it is limited to particles with known dimensions, which are much greater than the radiation wavelength. Under this condition, the extinction cross section is dependent only on the geometrical cross section of the particle and not on the optical properties of the material. This method is known as the geometric optic

inversion (GOI) technique. Simply stated, it computes the extinction cross section at short wavelengths using geometric optics and combines this with a measure of transmittance at the short wavelengths and pathlengths to compute concentration, which is then used to compute the extinction cross section at the longer wavelengths.

There are three conditions that must be adhered to when using the geometric optic inversion technique. First, the incident transmissometer energy must have a wavelength that is considerably shorter than the radius of the aerosol particle.[1] Second, the particles in the cloud must be randomly oriented. Finally, the particles must be monodisperse, that is, no distribution in size of primary particles and no agglomerates. If the size, shape, and density distribution of a polydispersion of primary particles and agglomerates were accurately characterized, the calculations could be adapted, but this is never the case in practice.

The first condition for using the geometric optics inversion technique can be met by using a 0.63 μ HeNe laser as the illuminating source with a monodisperse fiber aerosol with a diameter >3 μ. This corresponds to aerodynamic diameters >15 μ for materials with densities around 2 g/cm^3.[2] Random orientation can be expected in a chamber that has stirring fans to create a constant and turbulent movement of air within the chamber. Random orientation is demonstrated when vertical and horizontal, polarized, microwave-transmittance measurements are equal. Based on scanning electron microscope data of cloud samples, clumping of particles can be ignored if the start of data acquisition is delayed for sufficient time for the clumps to fall out of the cloud.

3. DERIVATION OF EQUATIONS

The equations required for this technique will now be derived. The extinction coefficient (α) can be defined as the electromagnetic extinction cross section (C_E) per unit mass (M) of aerosol.

$$\alpha = \frac{C_E}{M} \tag{2}$$

The extinction cross section may be written in terms of the geometric cross section (G) and extinction efficiency factor (Q) of the particle.[3]

$$C_E = GQ \tag{3}$$

Therefore,

$$\alpha = \frac{GQ}{M} \tag{4}$$

For a randomly oriented convex particle, the average projected area ($\overline{G}$) depends only on the surface area (S).[1]

$$\overline{G} = \frac{S}{4} \tag{5}$$

When the particle dimensions are much greater than the measuring wavelength, geometric optics states [1] that

$$Q = 2 \tag{6}$$

By definition, particle mass is related to particle density (ρ) and volume (V) by

$$M = \rho V \tag{7}$$

thus α averaged over a randomly oriented particle ensemble becomes

$$\bar{\alpha} = \frac{S}{2\rho V} \tag{8}$$

The surface area-to-volume ratio of a fiber having length (l) and radius (r) is

$$\frac{S}{V} = \frac{2\pi r l}{\pi r^2 l} = \frac{2}{r} \tag{9}$$

Thus, the extinction coefficient for a monodisperse randomly oriented ensemble of fibers in the geometric optics limit is [4]

$$\bar{\alpha} = \frac{1}{\rho r} \tag{10}$$

If density is expressed in grams per cubic centimeter, and r in microns, then the extinction coefficient is given in square meters per gram.

The equation relating C, L, T, and α follows:

$$\bar{\alpha} = \frac{\ln\left(\frac{1}{T}\right)}{CL} \tag{11}$$

We can now calculate C in grams per cubic meter by substitution of the $\bar{\alpha}$ derived earlier for the geometric optic region and by using the following set of convenient units:

$$C\left[\frac{g}{m^3}\right] = \frac{\rho\left[\frac{g}{cm^3}\right] r[microns] \ln\left(\frac{1}{T_{0.63}}\right)}{L[m]} \tag{12}$$

where $T_{0.63}$ is T at 0.63 μ wavelength.

This value of the concentration can now be used, along with transmissometry data, to calculate the extinction coefficient at longer wavelengths outside of the geometric optics region by substitution into the equation relating $\bar{\alpha}$ to C, L, and T:

$$\bar{\alpha}_\lambda = \frac{L_{0.63} \ln\left(\frac{1}{T_\lambda}\right)}{L_\lambda \, \rho r \ln\left(\frac{1}{T_{0.63}}\right)} \tag{13}$$

where T_λ and L_λ are now the transmittance and pathlength at a longer wavelength. The pathlengths of the laser and longer wavelength beams are included in the above equation because it is often necessary to change pathlengths as a function of wavelength to stay within the transissometer dynamic range. If the pathlengths are the same, then the pathlength ratio drops out of the equation. When we satisfy the three conditions mentioned earlier and use the geometric optic inversion, we bypass the need for a difficult mass aerosol filter sample.

Large aerodynamic diameter fibers do not normally attenuate well in the visible region of the spectrum. When measuring the laser transmission through an aerosol cloud of high-aspect-ratio particles, it will help considerably if the laser beam passes through the cloud more than once. This can be effected with mirrors. Every pass of the beam through the cloud results in additional transmission loss but has the effect of increasing the signal-to-noise ratio ot the laser detector output. Of course, the additional pathlength of the beam must be taken into account when calculating the concentration.

4. EXPERIMENTAL VERIFICATION

Attempts have been made to correlate the concentration of large aerodynamic diameter fibers, as calculated by the GOI method, with other means of concentration measurement, with hopes to establish an absolute method. One series of tests used a coated screen on top of a horizontal filter sampler. Fibers striking the screen stuck to it, and both the screen and filter were weighed before and after the test. Comparison of the filter data with the geometric optic inversion data showed that the GOI concentration was about 1.3 times the coated screen/filter concentration.

Another technique for measuring the concentration was to use a thimble filter, which is a long tubular filter that traps sampled material on it and prevents it from falling off the filter. A comparison of the data collected is shown in Table 1. The filter concentration (C_f) is calculated using Equation (1). The GOI concentration (C_{GOI}) is calculated by using the transmittance ($T_{0.63}$) averaged over the duration of each filter sample and Equation (12). Using $T_{0.63}$ as a real-time indicator, C_{GOI} was maintained around 100 mg/m^3. The filter inlet opening is 15/16 in., and the volumetric flow rates ($\dot{V}$) through the thimble filter are listed. The ratio of C_f to C_{GOI} is shown for each sample flow rate.

Table 1

$\dot{V}$ (LPM)	Ratio of C_f/C_{GOI}
30	.75
40	.84
50	.90
60	.91
70	.86
80	.79
90	.71

Table 1. Concentration Ratio Versus Sampling Flow Rate

The data from Table 1 is plotted below (Figure 1).

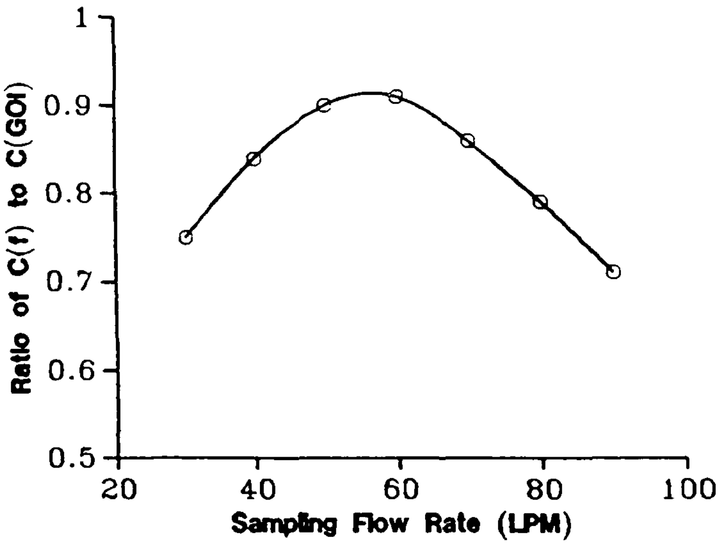

Figure 1. Plot of Concentration Ratio Versus Sampling Flow Rate

Table 1 and Figure 1 show that, at a sample flow rate between 50 and 60 liters per minute (LPM), the ratio of filter concentration to GOI-calculated concentration is around 90%. In other words, the GOI concentration is 1.1 times the filter concentration at optimum sampling flow rates. The change in the ratio versus flow rate shown in Table 1 and Figure 1 reflects the performance of the thimble filter, which appears to be sampling-velocity dependent. However, the closeness of the two concentrations at 60 LPM sampling flow rate, within 10%, indicates that the GOI technique is a good concentration approximation. The technique appears to be a good solution to a difficult sampling problem with the advantage of being a real-time measurement. The GOI method is considerably faster and easier, which combined with its close agreement to the filter technique (at optimum sampling velocity) justifies its use for this special case of large particles. Future work will be directed at determining the basis for the concentration offset between the two techniques.

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